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A detailed description of the subhalo population of the Milky Way

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Abstract: In the standard model of cosmic structure formation, dark matter halos form by gravitational instability. The process is hierarchical: smaller systems collapse earlier, and later merge to form larger halos. The probability that a halo of mass m at redshift z will be part of a larger halo of mass M at the present time is described by the progenitor (conditional) mass function $f(m, z|M, z_0 = 0)$, according to the so called extended Press & Schechter theory. Using the progenitor mass function we calculate analytically, at redshift zero, the distribution of subhalos in mass, formation epoch and rarity of the peak of the density field at the formation epoch. That is done for a Milky Way-size system, assuming both a spherical and an ellipsoidal collapse model. Our calculation assumes that small progenitors do not loose mass due to dynamical processes after entering the parent halo, nor that they interact with other subhalos. For a LCDM power spectrum we obtain a subhalo mass function dn/dm proportional to $m^{-\alpha}$ with a model-independent $\alpha \sim 2$, confirming what is found in N-body simulations. The inferred distributions is used to test the feasibility of indirect detection of such a population of subhalos with modern experimental tecniques.

Introduction

The present-day description of the universe includes 26 % of cold dark matter (CDM), whose nature and distribution is unknown [1]. No dark matter (DM) particle has been observed so far, although hypotheses have been done on weakly interacting massive particles (WIMPs) coming from Supersymmetry or Universal Extra Dimension theories. The distribution of DM inside the halos is uncertain too. Numerical N-body simulations and experiments do not have enough resolution to study the very inner part of the DM halos, nor to give exact predictions for the effect of baryons and black holes. In the hierarchical formation scheme of the CDM scenario, large systems are the result of the merging and accretion of highly concentrated subhalos. In such dense areas, the DM annihilation into standard model particles is expected to give the bigger contibution.
References and further details can be found in [2].

In this paper we discuss an analytical approach to the subhalos population in DM halos using extended-Press & Schechter theory [3, 4]. We integrate both spherical and ellipsoidal collapse progenitors mass function at all redshifts. We estimate the upper bound for the contribution to the γ-ray flux due to the presence of a population of subhalos inside the Milky Way; and we study the prospects for detection of substructures with a GLAST-like experiments in our best case scenario.

From Progenitors to Subhalos

We discuss here an analytical approach to derive the mass function of subhalos, in the simplifying assumption that no tidal stripping or merging events happen among substructures. For the complete list of references we refer to [5].

In this approach, the mass of each subhalo remains constant in time, and it equals the original virial mass of the system at the time when it was accreted by the larger halo.

Let us consider a halo with virial mass M at some final redshift z_0. In the hierarchical picture of galaxy formation the halo will be splitted in smaller and smaller systems, called "progenitors", while going backward in time.

The progenitors mass function is represented by the conditional mass function $f(s, \delta_{sc}|S, \delta_0)\mathrm{d}s$, where $s = \sigma^2(m)$ is the square of the mass variance of a halo with mass m, and δ_{sc} is the spherical collapse overdensity at redshift z. S and δ_0 are the corrisponding values for the mass variance of a halo of mass M and the spherical collapse overdensity at the present time. The influence of sourrounding proto-halos is though important and can be reproduced using an ellipsoidal collapse model [6, 7]. We refer to [3] for the distribution in the spherical collapse model and to [7] for the ellipsoidal one. The spherical collapse underpredicts (overpredicts) the abundance of large (small) mass halos. In fact, fixing the mass while going back in time (higher redshifts) results in a prediction of too many small halos and too few large ones, compared to the ellipsoidal case and to N-body simulations. A direct consequence of this is that in the ellipsoidal collapse massive progenitors exist at higher redshifts, and so the distribution of formation redshifts (defined as the earliest epoch when a halo assembles half of its final mass in one system) is shifted to earlier epochs [8].

From $f(s, \delta_{sc}|S, \delta_0)\mathrm{d}s$ we can write the total number of progenitors at some given redshift as:

$$N(m, \delta_{sc}|M, \delta_0)\mathrm{d}m = \frac{M(S)}{m(s)} f(s, \delta_{sc}|S, \delta_0)\mathrm{d}s \,. \tag{1}$$

Integrating the progenitors mass function for the spherical collapse model over δ_{sc}, gives the total number of progenitors of mass m that a halo of final mass M has had at all times:

$$\frac{\mathrm{d}n(m)}{\mathrm{d}m} = \int_{\delta_0}^{\infty} \frac{M}{m} f(s, \delta_{sc}|S, \delta_0)\mathrm{d}\delta_{sc}\,; \tag{2}$$

this integral can be solved analytically, giving:

$$\frac{\mathrm{d}n(m)}{\mathrm{d}\ln(m)} = \frac{M}{\sqrt{2\pi}} \frac{|\mathrm{d}s/\mathrm{d}m|}{\sqrt{s-S}} \propto m^{-\alpha}\,, \tag{3}$$

with $\alpha \approx 1$ for a LCDM power spectrum.

We take into account double-countings of halos by imposing the constraint that roughly 10% of the total Milky Way mass ($M = 10^{12} M_\odot/h$) is in systems with mass ranging from 10^7 to $10^{10}\, M_\odot/h$ [9].

In the upper panel of Fig. 1 we plot the differential distribution of subhalos in a $10^{12}\, M_\odot/h$ (Milky Way like) DM halo. Its power law behaviour can be approximately described by a slope ≈ -1.

Using high resolution N-body simulations, the authors of [10] studied the distribution - at $z = 0$ - of matter belonging to high redshift progenitors of a given system. They found that this distribution mainly depends on the rareness of the density peak corresponding to the progenitor, expressed in terms of $\nu\sigma(M, z)$, and is largely independent on the particular values of z and M. The higher is ν, the more concentrated is the distribution of matter in the final system. We have then computed $\nu(m, z) = \delta_{sc}(z)/\sigma(m)$ for each progenitor, in a given mass bin at fixed redshift. In the lower panel of Fig. 1 we plot the distribution in term of ν for progenitors in the smallest and biggest decade of mass we have considered, integrated over redshift.

Indirect detection of subhalos

The annhilation flux $\Phi = \Phi^{\mathrm{PP}} \times \Phi^{\mathrm{cosmo}}$ is factorized into two terms referring to particle physics and cosmological contributions. The latter term includes cosmology as well as experimental details such as the angular resolution $\Delta\Omega$ and the angle of view from the Galactic Center (GC) ψ, and is defined as

$$\Phi^{\mathrm{cosmo}}(\psi,\Delta\Omega) = \int_M dM \int_\nu d\nu \int\int_{\Delta\Omega} d\theta d\phi \int_{\mathrm{l.o.s}} d\lambda$$
$$\left[\rho_{sh}(M, R(R_\odot\lambda,\psi,\theta,\phi),\nu) \times P(\nu(M)) \times\right.$$
$$\left.\times \Phi^{\mathrm{cosmo}}_{halo}(M,\nu,r(\lambda,\lambda',\psi,\theta',\phi')) \times J(x,y,z|\lambda,\theta,\phi)\right] \tag{4}$$

where

$$\Phi^{\mathrm{cosmo}}_{halo}(M,\nu,r) = \int\int_{\Delta\Omega} d\phi' d\theta' \int_{\mathrm{l.o.s}} d\lambda'$$
$$\left[\frac{\rho_\chi^2(M,\nu,r(\lambda,\lambda',\psi,\theta',\phi'))}{\lambda^2} J(x,y,z|\lambda',\theta'\phi')\right] \tag{5}$$

ρ_{sh} is taken from [10], ρ_χ is the NFW density profile inside the halo. $P(\nu(M))$ is the normalized probability of finding a halo of mass M with a

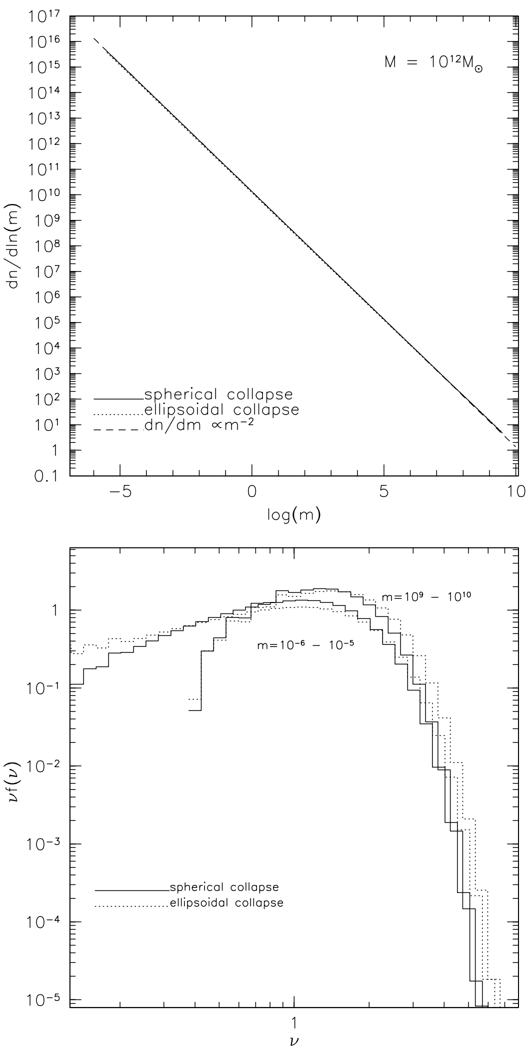

Figure 1: Upper panel: differential distribution of subhalos in a $10^{12}\,M_\odot/h$ DM halo. A least-squares fit on the points gives $\alpha_{\rm sc} = -0.9972 \pm 0.0001$ and $\alpha_{\rm ec} = -0.9937 \pm 0.0003$ for the spherical and ellipsoidal collapse model, respectively. Lower panel: subhalo distribution in term of $\nu = \delta_{sc}/\sigma(m)$ for the smallest and biggest decades of mass considered in the analysis.

given ν. We refer to [5] for the complete definition of symbols and we show the results for $\Phi^{\rm cosmo}$ as a function of ψ in the upper panel of Fig.2, where the MW clumpy and smooth foregrounds are computed using Eq. 4 and 5, respectively. Results are shown for the ellipsoidal model but do not change significantly when the spherical collapse is used instead. ρ_χ is a function of the concentration parameter $c(M,\nu,z)$. In Fig.2 we show two different models for c, which we take from [11]. The Bz0 model computes scale parameters in ρ_χ at z=0, while the Bzf one fixes them at the formation redshift, resulting in a higher inner density. To compute the $\gamma-$ray flux we use an optimistic value of the particle physics contribution

$$\Phi^{\rm PP}(E_\gamma) = \frac{1}{4\pi}\frac{\sigma_{\rm ann}v}{2m_\chi^2} \times \sum_f B_f \int_E \frac{dN_\gamma^f}{dE_\gamma}dE. \quad (6)$$

We adopt $m_\chi = 40$ GeV, $\sigma_{\rm ann}v = 10^{-26}$cm^{3}s^{-1}, a 100% branching ratio in $b\bar{b}$ and the $dN_\gamma^{b\bar{b}}/dE_\gamma$ functional form of [12]. The two c models are then compared with the EGRET data and the Bzf one is reduced accordingly since it was found to exceed the measured extragalactic diffuse data [5].

We then compute the experimental sensitivity of a GLAST-like experiment defined as the ratio of the number of annihilation photons to the astrophysical background fluctuation $\sigma = \frac{n_\gamma}{\sqrt{n_{bck}}}$. The background contribution is computed according to [13, 14]. Again, we refer to [5] for a discussion of the experimental details. The sensitivity as a function of ψ is plotted in the lower panel of Fig.2. A zoom toward the GC is shown in the small superimposed frame, to better appreciate the small angle sensitivity.

Discussion and conclusion

We have derived an analytical description of the distribution of rareness of density peaks in the subhalo population of our Galaxy. This has allowed to shape and model the total diffuse annihilation γ-ray flux we expect to detect with a GLAST-like experiment. Using the best case particle physics scenario, the only free parameter is the concentration of the single subhalos. We bracket its effect using two models which result in very different inner densities inside the halos. Our results on detectability show that a detection is possible toward

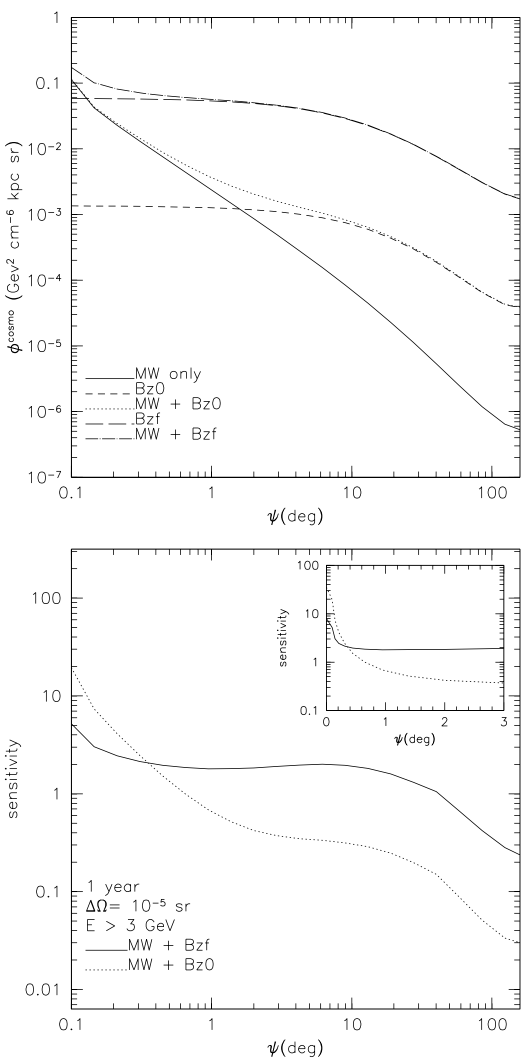

Figure 2: Upper panel: subhalo contribution to the γ-ray flux for different models of the concentration parameters. MW smooth and clumpy contributions are shown separately, together with their sum. Lower panel: sensitivity curves for the same models for a GLAST-like experiment. A zoom at small angles is provided in the superimposed frame.

the GC for both models, and it would be impressive for the Bz0 one. A 2-σ effect would show up as well, simmetrically distributed up to $\sim 20^\circ$ around the GC, only for the Bzf model. Unfortunately, a reliable modeling of the astrophysical background coming from the GC and of the effect of the central Super Massive Black Hole on the inner DM density profile are poorly known, and are mayor ingredients for our calculations. Yet, we can point out that, in our scenario, the existence of a population of subhalos would be likely to be detected in 1 year of effective data taking with a GLAST-like experiment.

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